SuperWIMP dark matter and 125 GeV Higgs boson in the minimal GMSB

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Recently, both the ATLAS and CMS experiments have observed an excess of events that could be the first evidence for a 125 GeV Higgs boson. We investigate an implication of the CP-even Higgs boson with mass around 125 GeV in the context of the minimal gauge mediated supersymmetry breaking (mGMSB). In mGMSB, gravitino is the lightest sparticle (LSP) and hence the dark matter candidate. We consider the so-called superWIMP scenario where the dark matter gravitino is non-thermally produced by the decay of the next-to-LSP (NLSP) bino-like neutralino after its freeze-out. For a given $\tan\beta$ and the number of the messengers (N_m) fixed, we find that the rest of the mGMSB parameters, the SUSY breaking parameter and the messenger scale, are completely fixed by the conditions of simultaneously realizing the observed dark matter abundance and the 125 GeV Higgs boson mass, leading to the NLSP neutralino mass around $1.5-2$ TeV and the gravitino mass around $3-7$ GeV, depending on the values of $\tan\beta$ and N_m. The lifetime of the NLSP is found to be shorter than 1 sec, so that the success of the big bang nucleosynthesis remains intact. The non-thermally produced gravitino behaves as the warm dark matter with the free-streaming scale found to be $\lambda_{\rm FS} \simeq 0.1$ Mpc, whose value is reasonable for observations of the power spectrum on both large and sub-galactic scales in the Universe.

The low energy supersymmetry (SUSY) is arguably one of the most promising candidates for new physics beyond the Standard Model (SM). The minimally supersymmetric extension of the SM (MSSM) provides us with not only a solution to the gauge hierarchy problem but also various interesting phenomena such as the successful SM gauge coupling unification, the radiative electroweak symmetry breaking, prediction of the SM-like Higgs boson mass, and a candidate for the dark matter in our Universe. It has been expected that some of sparticles can be discovered in the near future, most likely at the Large Hadron Collider (LHC).

As well as the discovery of new particles, the discovery of the Higgs boson is another major goal of the physics program at the LHC, in order to confirm the origin of the electroweak symmetry breaking and the mechanism of particle mass generation. Recently, the ATLAS [1] and CMS [2] experiments have reported an excess of evens that could be the first evidence of the Higgs boson with mass of around 125 GeV [3]. The observations are supported by recent analysis of the Tevatron experiments [3]. The 125 GeV Higgs boson has a great impact on SUSY phenomenology, because the MSSM has a prediction of the SM-like Higgs boson mass as a functions of soft SUSY breaking parameters, in particular, stop masses. Detailed studies for realizing the Higgs mass around 125 GeV is a current hot topic in SUSY phenomenology [4]. In most of the studies, the constrained MSSM (CMSSM) or slight extention of the CMSSM is adopted for the boundary conditions on the soft SUSY parameters at the scale of the grand unified theory (GUT).

Although the CMSSM or more generally, the context of supergravity mediated SUSY breaking is a very simple benchmark in examining the sparticle mass spectrum, this scenario potentially suffers from the SUSY flavor problem [5]. The gauge mediated SUSY breaking (GMSB) [6] offers the compelling resolution for the SUSY flavor problem due to the SUSY breaking mediation via the flavor-blind SM gauge interactions. In this paper, we investigate an implication of the 125 GeV Higgs in the context of the mGMSB. There were several studies on this context [7], and very recently a more comprehensive studies with the parameter scan has been performed [8]. Although these studies identified a parameter space to realize the Higgs mass around 125 GeV, phenomenology of the gravitino dark matter has not been studied in detail. In this paper, we complete our study on the mGMSB by considering not only the realization of 125 GeV Higgs mass but also the the gravitino dark matter phenomenology, in particular, the so-called superWIMP scenario. We will show that once the values of $\tan\beta$ and the number of messengers (N_m) are fixed, the sparticle mass spectrum is completely determined and the resultant sparticle mass spectrum is consistent with all phenomenological constraints.

In the mGMSB, we introduce the superpotential for the messenger sector,

$$W_{mess} = \sum_{i=1}^{N_m} S\overline{\Phi}_i\Phi_i, \qquad (1)$$

where S is a chiral superfield in the hidden sector with $\langle S\rangle = M + \theta^2 F$, and $\overline{\Phi}_i$ and Φ_i are a vector-like pair of messengers of the $\bar{\mathbf{5}}+\mathbf{5}$ representation under the SU(5) GUT gauge group. For simplicity, we use the SU(5) GUT notation throughout the paper. In order to maintain the successful SM gauge coupling unification, a pair of messengers should be in a complete SU(5) representation and have an SU(5) invariant mass term.

Soft SUSY breaking terms can be extracted from the SUSY wave function renormalization coefficients with the threshold corrections by the messengers [9]. The MSSM gaugino masses at a scale $\mu \leq M$ is given by (we assume $F \ll M^2$)

$$M_i(\mu) = \frac{\alpha_i(\mu)}{4\pi}\Lambda N_m, \qquad (2)$$

where $i = 1, 2, 3$ correspond to the SM gauge interactions of SU(3), SU(2) and U(1)$_Y$, respectively, and $\Lambda = F/M$ is the SUSY breaking parameter. When we neglect Yukawa coupling contributions, the MSSM scalar squared masses at

$\mu \leq M$ are given by

$$m_{\tilde{f}}^2(\mu) \ = \ \sum_i 2C_i \left(\frac{\alpha_i(\mu)}{4\pi}\right)^2 \Lambda^2 \ N_m \ G_i(\mu, M), \quad (3)$$

where $G_i(\mu, M) = \xi_i^2 + \frac{N_m}{b_i}(1-\xi_i^2)$ with $\xi_i = \alpha_i(M)/\alpha_i(\mu)$. Here b_i are the beta function coefficients for different SM gauge groups, C_i are the quadratic Casimir, and the sum is taken corresponding to the representation of the sparticles under the SM gauge groups. The messenger has no contribution to A-parameter at the messenger scale, $A(M) = 0$. In the following numerical analysis, we employ the SOFTSUSY 3.3.1 package [10] to solve the MSSM RGEs and produce mass spectrum, where the following free parameters are defined at the messenger scale:

$$N_m, M, \Lambda, c_{\rm grav}, \tan\beta, {\rm sign}(\mu). \quad (4)$$

For simplicity, we set $\mu > 0$. In our analysis we assume $c_{\rm grav} = 1$, which means F is the dominant SUSY breaking source. In this case, gravitino mass is given by

$$m_{\tilde{G}} = \frac{M\Lambda}{\sqrt{3}M_P}, \quad (5)$$

where $M_P = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. Since flavor-dependent supergravity contributions to sfermion masses are estimated as $\Delta m_{\tilde{f}}^2 \sim m_{\tilde{G}}^2$, we need to set $m_{\tilde{G}}^2 \ll m_{\tilde{f}}^2$, equivalently, $M \ll 10^{16}$ GeV, to make the flavor-independent GMSB contributions dominant. Therefore, gravitino is always the LSP and hence the dark matter candidate. From Eqs. (2) and (3) we see that the NLSP is most likely bino-like neutralino for $N_m = \mathcal{O}(1)$.

As is well known, stop loop corrections play a crucial role to push up the SM-like Higgs boson mass from its tree-level value, $m_h \simeq m_Z \cos 2\beta$. Since the corrections logarithmically depend on stop mass, a large stop mass of $\mathcal{O}$(10 TeV) is necessary to realize $m_h \simeq 125$ GeV. This corresponds to $\Lambda \sim 10^6$ GeV from Eq. (3) and mass of the NLSP bino-like neutralino to be $m_{\tilde{B}} \sim 1$ TeV from Eq. (2), for $N_m = \mathcal{O}(1)$.

Now let us consider phenomenology for the gravitino dark matter. This is quite different from the usual one with the dark matter as a weakly interacting massive particle (WIMP), because gravitino couples to the MSSM particles super-weakly and (unless the gravitino is light, say $m_{\tilde{G}} \lesssim 1$ keV) it has never been in thermal equilibrium in history of the Universe. This fact brings uncertainty in evaluating the relic abundance of the dark matter and thus one may think this scenario less interesting. However, there is a very appealing possibility with a super-weakly interacting dark matter particle, the so-called superWIMP scenario [11, 12] (see also [13] for the superWIMP scenario in non-standard cosmology). In this scenario, the superWIMP dark matter is mainly produced via the decay of a long-lived WIMP, so that its relic abundance is given as

$$\Omega_{DM} h^2 = \Omega_X h^2 \times \left(\frac{m_{DM}}{m_X}\right), \quad (6)$$

where $\Omega_X h^2$ would be the thermal relic abundance of the long-lived WIMP (X) if it were stable. In this scenario, nevertheless the superWIMP has never been in thermal equilibrium, its relic abundance is calculable as in the usual WIMP dark matter scenario.

We adopt the superWIMP scenario in the mGMSB, where the superWIMP is the LSP gravitino and the WIMP X is the bino-like neutralino. Note that bino-like neutralino, if it were the LSP, tends to be over-abundant because of its small annihilation cross section. Therefore, the suppression factor $m_{\tilde{G}}/m_{\tilde{B}} \ll 1$ can work well to adjust $\Omega_{DM}h^2$ to be the observed value [14]. With a fixed $\tan\beta$ and N_m, we first calculate particle mass spectrum by SOFTSUSY 3.3.1 package for various values of M and Λ. Then, the relic abundance of the NLSP neutralino is calculated by using the micrOMEGAs 2.4.5 [15] with the output of SOFTSUSY in the SLHA format [16]. Multiplying by the factor $m_{\tilde{G}}/m_{\tilde{B}}$, we finally obtain the relic abundance of the gravitino dark matter.

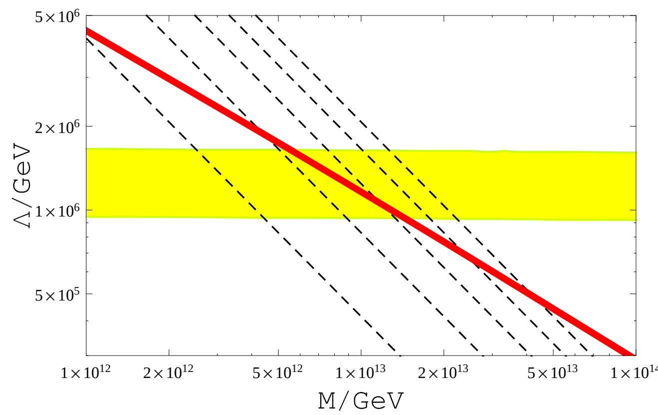

FIG. 1: Contours on the (M, Λ)-plane for $\tan\beta = 10$ and $N_m = 1$. The dark shaded region (in red) and the horizontal shaded region (in yellow) satisfy the constraints of the observed dark matter abundance ($0.1064 \leq \Omega_{\tilde{G}}h^2 \leq 0.1176$) and the SM-like Higgs boson mass (124 GeV $\leq m_h \leq$ 126 GeV), respectively.

Fig. 1 shows our numerical results in the (M, Λ)-plane, for $\tan\beta = 10$ and $N_m = 1$. In the dark shaded region (in red), the resultant gravitino relic abundance is consistent with the observed value [17], $\Omega_{\tilde{G}}h^2 = 0.1120 \pm 0.0056$. The parameter sets in the horizontal shaded region (in yellow) predict the SM-like Higgs boson mass in the range of 124 GeV $\leq m_h \leq$ 126 GeV. The dashed lines correspond to the gravitino mass $m_{\tilde{G}} = 1, 2, 3, 4,$ and 5 GeV, respectively, from left to right. The parameter region which simultaneously satisfies the observed Higgs boson mass and the dark matter relic abundance can be pined down by the overlap of the two shaded regions, $(M, \Lambda) \simeq (9.2 \times 10^{12}\ {\rm GeV}, 1.2 \times 10^6\ {\rm GeV})$.

Here we give a semi-analytical explanation of our results. The relic abundance of the bino-like neutralino is well approx-

imated as [18]

$$\Omega_{\tilde{B}}h^2 \simeq \frac{8.7\times 10^{-11}\ \mathrm{GeV}^{-2}\ (n+1)x_f^{n+1}}{\sqrt{g_*}\sigma_{\tilde{B}}}, \tag{7}$$

where $n = 1$, $x_f = m_{\tilde{B}}/T_f \sim 20$ is the freeze-out temperature, and $\sigma_{\tilde{B}}$ is the pair annihilation cross section of the bino-like neutralino through the exchange of the right-handed charged sleptons in the t-channel,

$$\sigma_{\tilde{B}} \simeq \frac{3g^4\tan^4\theta_W r(1+r^2)}{2\pi m_{\tilde{e}_R}^2(1+r^4)} \tag{8}$$

with $r = (M_1/m_{\tilde{e}_R})^2$. Using Eqs. (2) and (3), we can check that the factor $r(1+r^2)/(1+r^4)$ is almost constant ~ 0.12 for various values of $N_m = \mathcal{O}(1)$ and $M = 10^{12-14}$ GeV. Thus, we find

$$\Omega_{\tilde{G}}h^2 \simeq \Omega_{\tilde{B}}h^2 \times \left(\frac{m_{\tilde{G}}}{M_1}\right) \propto m_{\tilde{e}_R}^2\frac{m_{\tilde{G}}}{M_1} \propto M\Lambda^2. \tag{9}$$

Since sfermion masses logarithmically depend on the messenger scale (see Eq. (3)), the predicted Higgs mass determined by stop masses is almost independent of $M = 10^{12-14}$ GeV.

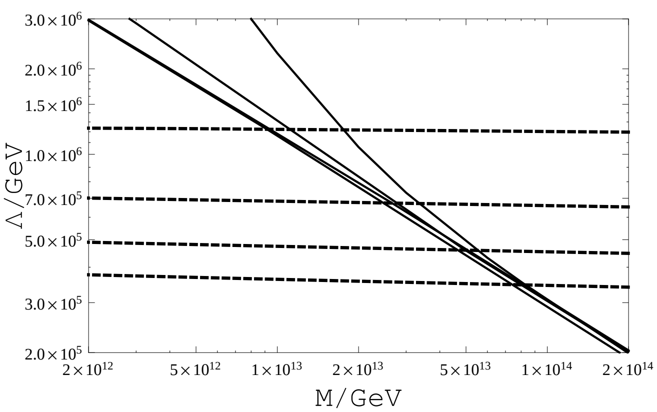

FIG. 2: Contours on the (M, Λ)-plane for $\tan\beta = 10$ and $N_m = 1, 2, 3, 4$. The solid lines correspond to the region satisfying $\Omega_{\tilde{G}}h^2 = 0.112$, from left to right for $N_m = 1, 2, 3, 4$, respectively. Along the dashed lines the SM-like Higgs boson mass is predicted to be $m_h = 125$ GeV, from top to bottom for $N_m = 1, 2, 3, 4$, respectively.

We repeat the similar numerical analysis for various values of N_m and $\tan\beta$. Fig. 2 depicts the results for $N_m = 1, 2, 3, 4$, with $\tan\beta = 10$. The solid lines show the contours along which $\Omega_{\tilde{G}}h^2 = 0.112$ is satisfied, from left to right corresponding to $N_m = 1, 2, 3, 4$, respectively. All lines are very close to each other except that the line for $N_m = 4$ is substantially deviating from the other lines for $M \lesssim 5\times 10^{13}$ GeV. This is because for such a parameter region, the NLSP bino-like neutralino becomes more degenerate with lighter stau as M is lowered, so that the co-annihilation process of the NLSP with the stau becomes more effective and reduces the abundance. In order to compensate this reduction and achieve the observed relic abundance, a relatively higher neutralino mass, equivalently a larger Λ is needed. The dashed horizontal lines correspond to the Higgs boson mass prediction $m_H = 125$ GeV, from top to bottom for $N_m = 1, 2, 3, 4$, respectively. We find that stau becomes the NLSP for $N_m \geq 5$. The annihilation process of the NLSP stau is very efficient, so that the suppression factor $m_{\tilde{G}}/m_X$ makes the gravitino abundance too small. Hence, we do not consider the case with $N_m \geq 5$.

$\tan\beta$	10			45
N_m	1	2	4	1
M	9.16×10^{12}	2.66×10^{13}	8.28×10^{13}	1.51×10^{13}
Λ	1.23×10^{6}	6.73×10^{5}	3.47×10^{5}	1.05×10^{6}
h_0	125			
H_0	7123	6304	5607	4418
A_0	7123	6304	5607	4419
$H^\pm$	7123	6304	5608	4419
$\tilde{g}$	7726	8300	8424	6719
$\tilde{\chi}^0_{1,2}$	1693, 3141	1856, 3424	1909, 3509	1454, 2707
$\tilde{\chi}^0_{3,4}$	5147, 5148	4717, 4719	4365, 4369	4370, 4372
$\tilde{\chi}^\pm_{1,2}$	3141, 5149	3424, 4719	3509, 4369	2707, 4372
$\tilde{u}, \tilde{c}_{1,2}$	9227, 10123	8491, 9193	7837, 8389	7983, 8757
$\tilde{t}_{1,2}$	7274, 9260	6829, 8455	6413, 7745	6296, 7695
$\tilde{d}, \tilde{s}_{1,2}$	9034, 10123	8346, 9193	7733, 8389	7812, 8757
$\tilde{b}_{1,2}$	8990, 9258	8308, 8452	7698, 7742	7107, 7693
$\tilde{\nu}_{e,\mu}$	4989	4242	3580	4330
$\tilde{\nu}_\tau$	4976	4231	3571	4084
$\tilde{e}, \tilde{\mu}_{1,2}$	3305, 4990	2783, 4243	2290, 3581	2895, 4330
$\tilde{\tau}_{1,2}$	3267, 4977	2750, 4232	2262, 3572	2070, 4087
$m_{\tilde{G}}$	2.66	4.24	6.81	3.77
$\Omega_{\tilde{G}}h^2$	0.112			

TABLE I: Particle mass spectra (in GeV) for various N_m and $\tan\beta$. The fundamental parameters in the mGMSB, M and Λ, have been fixed so as to satisfy two independent conditions, $\Omega_{\tilde{G}}h^2 = 0.112$ and $m_h = 125$ GeV.

In Fig. 2, we can pin down the parameter sets (M, Λ) which simultaneously satisfy the two conditions, $\Omega_{\tilde{G}}h^2 = 0.112$ and $m_h = 125$ GeV, at the intersections of the solid and dashed lines, for each N_m value. In Table 1, we list particle mass spectra for $N_m = 1, 2, 4$. Here we also list the result for $N_m = 1$ and $\tan\beta = 45$ as another sample.

In the superWIMP scenario, the NLSP has a long lifetime and its late-time decay is potentially dangerous for the success of big bang nucleosynthesis (BBN). In our scenario, the NLSP is bino-like neutralino and its lifetime is estimated as [11]

$$\tau_{\tilde{B}} \simeq 0.74\ \mathrm{sec}\times\left(\frac{m_{\tilde{G}}}{1\ \mathrm{GeV}}\right)^2\left(\frac{1\ \mathrm{TeV}}{m_{\tilde{B}}}\right)^5 \tag{10}$$

for its main decay mode $\tilde{B} \to \gamma + \tilde{G}$. For the parameter sets we have determined, the formula leads to $\tau_{\tilde{B}} < 1$ sec. Therefore, the NLSP neutralinos decay before the BBN era ~ 1 sec and the success of BBN remains intact.

The gravitino dark matter is produced by the decay of the bino-like neutralino and carries a large kinetic energy when it is produced. Such a non-thermally produced dark matter behaves as a "warm" dark matter, rather than the cold dark matter (CDM). While the CDM scenario has made great success in the structure formation of the Universe at large scales > 1 Mpc, the recent high resolution N-body simulations showed that the CDM scenario predicts too much power on sub-galactic scales to be consistent with the observations. It has been pointed out [19] that this problem can be solved by a non-thermally produced dark matter if its comoving free-streaming scale ($\lambda_{\rm FS}$) at the time of the matter-radiation equality ($t_{\rm EQ} \simeq 2.0 \times 10^{12}$ sec) is around 0.1 Mpc.

The free-streaming scale of the gravitino dark matter can be calculated as [20]

$$\begin{aligned} \lambda_{\rm FS} &= \int_{\tau_{\tilde{B}}}^{t_{\rm EQ}} \frac{v(t')}{a(t')} dt \simeq 2 v_0 t_{\rm EQ} (1+z_{\rm EQ})^2 \\ &\times \log \left[\sqrt{1 + \frac{1}{v_0^2 (1+z_{\rm EQ})^2}} + \frac{1}{v_0 (1+z_{\rm EQ})} \right], \end{aligned} \quad (11)$$

where $z_{\rm EQ} \simeq 3000$ is the red shift at $t_{\rm EQ}$, and $v_0 \simeq \frac{T_0}{T_I} \frac{E_I}{m_{\tilde{G}}}$ is the current velocity of the gravitino dark matter with the present temperature of the cosmic microwave background T_0, the temperature of the Universe $T_I \simeq \sqrt{1\,{\rm sec}/\tau_{\tilde{B}}} \times 10^{-3}$ GeV, and the energy of the gravitino $E_I = m_{\tilde{B}}/2$ when the gravitino is produced from the NLSP neutralino decay. It is easy to find $v_0 \simeq 1.0 \times 10^{-7} \left(\frac{1\,{\rm TeV}}{m_{\tilde{B}}} \right)^{3/2}$, which is independent of the gravitino mass, and the free-streaming scale is

$$\lambda_{\rm FS} \simeq 0.18\,{\rm Mpc} \times \left(\frac{1\,{\rm TeV}}{m_{\tilde{B}}} \right)^{3/2}. \quad (12)$$

The mass spectra listed on Table 1 give the free-streaming scale $\lambda_{\rm FS} \simeq 0.1$ Mpc, which is nothing but the value suitable for solving the problem with the CDM scenario on sub-galactic scales.

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